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FUSION PRODUCT ENERGY SPECTRA IN BEAM HEATED D-D, D-T, AND D-^{3}HE PLASMAS*

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INTRODUCTION

One of the critical parameters in large scale fusion experiments is the ion speed distribution and its variation with changes in confinement and heating. Large plasma dimensions and high densities complicate direct measurement of this distribution since ions escaping to the wall are primarily those which undergo charge exchange in the outer plasma or those which have suffered many collisions and significant energy loss during their migration from the central plasma. Several previous works[1-5] have shown that neutron and proton fusion reaction products generate a spectral line which is fairly broad due to Doppler broadening. For Maxwellian reacting ions, the Doppler width is related to the mean ion energy by eq. 1 below.

$$\Delta E_3 = \sqrt{\frac{16 \ln 2 \, m_3 m_4 Q T}{\left(m_3 + m_4\right)^2}} \qquad (1)$$

where ΔE_3 is the full width at half maximum (FWHM) of the lighter reaction product; Q the energy released in the reaction, T the plasma temperature, m_3 and m_4 are the masses of the light and heavy reaction products respectively. Predictions of spectral shape and fusion product line width have been extended to non-Maxwellian plasmas by Bogdanov[2], Lehner and Pohl[6], to beam driven plasmas by Elevant[4], Scheffel[5] and Heidbrink[7] and to rotating plasmas by Scheffel[5].

Neutron spectrum measurements have confirmed the above model in experiments with Maxwellian deuterium plasmas[8,9] as well as deuterium-tritium plasmas[10-11]. Proton spectra due to the D-^{3}He reaction have also been determined experimentally[12-13], and measurements in non-Maxwellian plasmas have been reported[14-19].

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SPECTRUM SIMULATIONS

The results reported here are based on a Monte Carlo simulation of reactions[20] in which a variety of ion speed distributions and angular distributions were considered. In all cases the appropriate differential cross sections, based on the model of Peres[21], were used to weight each reaction during the accumulation of a simulated fusion product energy spectrum. In the case of D-D fusion the reaction was assumed anisotropic in the center-of-mass system (CMCS) and used the angular distribution from reference 6. In the other cases the reaction was assumed isotropic in the CMCS. Typically 10^5 to 10^6 simulated reactions were sampled in order to compile each fusion product energy spectrum. Details of the calculations and a more complete presentation of the results will be published elsewhere.

Several generic ion speed distribution functions were considered for plausible beam heated plasmas and the four whose results will be reported here are: 1) isotropic Maxwellian, 2) isotropic, monoenergetic, 3) monoenergetic beam incident on a Maxwellian target viewed at 0 degrees relative to the beam, and 4) a three component Gaussian distribution characteristic of injected neutral species whose atomic, diatomic, and triatomic components are broken up in the plasma into ions with energies equal to full, half, and one third energy components, respectively. In the latter case energy diffusion produces three Gaussian components in the speed distribution.

The three component Gaussian distribution function is described by the form given in eq. 2 below.

$$f\,(v) = \sum_{i=1}^{3} \frac{Bi}{Wi} e^{-1/2 \left(\frac{v-v_i}{W_i}\right)^2} \qquad (2)$$

where v_i are the speeds corresponding to the acceleration energy, Eb, and the partial energy components $E_b/2$ and $E_b/3$. B_i and w_i are parameters describing the relative populations of the injected species and their width due to energy diffusion. In all of the results presented the width parameters are constrained by eq. 3 below

$$W_i = \gamma V_i \qquad (3)$$

so that the speed distribution function is described completely by the parameters E_b, B_i and γ. All of the results summarized below were carried out with γ=.0425, based on experiments with injection into mirror confined plasmas, and B_i corresponding to injected species with 50% at full energy, 40% at half energy and 10% at one third energy.

RESULTS

Results of the simulations were compiled for a wide variety of mean ion energies and for all of the reaction types and ion speed distribution functions. Mean energy of the fusion reaction product energy spectrum was calculated in each case and the full-width-at-half-maximum (FWHM) determined. In addition, all moments about the mean up to order ten were calculated to determine the extent to which the result spectra were non-Gaussian. The Doppler width results may be approximated by a simple power law given by eq. 4 below

$$\Delta E = a \left(\bar{E}\right)^b \tag{4}$$

This approximation is simpler than those of Elevant[4] and Scheffel[5] and slightly less accurate. Nevertheless, this power law, together with the values of the constants given in Table I represent the data in these simulations within 3 % over most of the energy range 1-100 keV, and within 7 % in all cases.

Table I
Parameters used to describe Doppler width in eq. 4

Reaction	D(d,n) a	D(d,n) b	T(d,n) a	T(d,n) b	3He(d,p) a	3He(d,p) b
Maxwellian	64.5	.515	134.8	.512	116.4	.554
Monoenergetic	22.3	.676	55.0	.717	53.8	.620
Gaussian	33.3	.625	73.1	.650	67.8	.609
80 keV beam on Maxwellian	48.6	.548	118.2	.504	117.5	.524

Examination of the table shows that the square root dependence of the Doppler width on mean ion energy is a good approximation in most cases. In addition, the moments about the mean for the result spectra were compared to the moments for a Gaussian distribution and it was found that all of the result spectra are Gaussian to order ten at low ion energies (<20 keV) and are very nearly Gaussian to the highest energy considered.

CONCLUSIONS

Examination of the results and the constants in Table I indicate the Doppler width is proportional to the square root of mean ion energy, but the constant of proportionality varies widely among different generic speed distribution types. For example a line width for D-D neutrons of 75 keV corresponds to a 1.2 keV Maxwellian ion distribution but also to a 6 keV monoenergetic ion distribution. These variations are reduced at the highest ion energies but are substantial in every case. Consequently, a measured Doppler width for the fusion products of these reactions may not be used alone to infer the mean energy of reacting ions. The functional form of the ion speed distribution must be known apriori or through independent measurement in order to infer a mean ion energy from a fusion product spectrum measurement. Detailed spectroscopy is not helpful since all of the reaction product spectra in these simulations were found to be Gaussian to high order. Consequently additional parameters in the ion distribution function may not be obtained from the details of the fusion product energy spectrum in the cases considered here. This is unfortunate in some cases, but the resulting simplicity may be helpful in interpreting some fusion product spectra with poor statistics when the form of the ion speed distribution is known with confidence. Nevertheless, there are many other cases, not considered here, where anisotropic ion angular distributions produce fusion spectral lines which are not Gaussian[7]. In those cases, detailed spectroscopy may provide information on scattering of injected neutrals and beam slowing down.

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